

Autonomous and Autonomic Swarms

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Abstract

A watershed in systems engineering is represented by the advent of swarm-based systems that accomplish missions through cooperative action by a (large) group of autonomous individuals each having simple capabilities and no global knowledge of the group's objective. Such systems, with individuals capable of surviving in hostile environments, pose unprecedented challenges to system developers. Design and testing and verification at much higher levels will be required, together with the corresponding tools, to bring such systems to fruition. Concepts for possible future NASA space exploration missions include autonomous, autonomic swarms. Engineering swarm-based missions begins with understanding autonomy and autonomicity and how to design, test, and verify systems that have those properties and, simultaneously, the capability to accomplish prescribed mission goals. Formal methods-based technologies, both projected and in development, are described in terms of their potential utility to swarm-based system developers.

packs of wolves, etc. These groupings behave like swarms in many ways. With wolves, for example, the elder male and female (alpha male and alpha female) are accepted as leaders who communicate with the pack via body language and facial expressions. Moreover, the alpha male marks the territory of the pack, and excludes wolves that are not members of the pack.

The idea that swarms can be used to solve complex problems has been taken up in several areas of computer science, which we will briefly introduce in Section 2. The term "swarm" in this paper refers to a large grouping of simple components working together to achieve some goal and produce significant results. The term should not be taken to imply that these components fly (or are airborne); they may equally well be on the surface of the Earth, under the surface, under water, or indeed operating on other planets.

We will describe NASA's motivation for using swarms in future exploration missions. We will describe one particular mission, currently in the concept stage, and examine why this (and similar systems) must exhibit autonomic properties.

1. Introduction

We are all familiar with swarms in nature. The mere mention of the word "swarm" conjures up images of large groupings of small insects, such as bees (apiidae) or locusts (acrididae), each insect having a simple role, but with the swarm as a whole producing complex behavior.

Strictly speaking, such emergence of complex behavior is not limited to swarms, and we see similar complex social structures occurring with higher order animals and insects that don't swarm *per se*: colonies of ants, flocks of birds,

2. Swarms and Intelligence

Swarms consist of a large number of simple entities that have local interactions (including interactions with the environment) [2]. The result of the combination of simple behaviors (the microscopic behavior) is the emergence of complex behavior (the macroscopic behavior) and the ability to achieve significant results as a "team" [4].

Intelligent swarm technology is based on swarm technology where the individual members of the swarm also exhibit independent intelligence [3]. With intelligent swarms,

members of the swarm may be heterogeneous or homogeneous. Even if members start as homogeneous, due to their differing environments they may learn different things, develop different goals, and therefore become a heterogeneous swarm. Intelligent swarms may also be made up of heterogeneous elements from the outset, reflecting different capabilities as well as a possible social structure.

Agent swarms are being used as a computer modeling technique and have also been used as a tool to study complex systems [12]. Examples of simulations that have been undertaken include swarms of birds [5, 16], as well as business and economics [15] and ecological systems [20].

In *swarm simulations*, each of the agents is given certain parameters that it tries to maximize. In terms of bird swarms, each bird tries to find another bird to fly with, and then flies off to one side and slightly higher to reduce its drag. Eventually the birds form flocks. Other types of swarm simulations have been developed that exhibit unlikely emergent behavior. These emergent behaviors are the sums of often simple individual behaviors, but, when aggregated, form complex and often unexpected behaviors. Swarm behavior is also being investigated for use in such applications as telephone switching, network routing, data categorizing, and shortest path optimizations.

Swarm intelligence techniques (note the slight difference in terminology from "intelligent swarms") are population-based stochastic methods used in combinatorial optimization problems, where the collective behavior of relatively simple individuals arises from their local interactions with their environment to give rise to the emergence of functional global patterns. Swarm intelligence represents a metaheuristic approach to solving a wide variety of problems.

Swarm robotics refers to the application of swarm intelligence techniques to the analysis of swarms where the embodiment of the "agents" is as physical robotic devices.

3. NASA Swarm Technologies

Future NASA missions will exploit new paradigms for space exploration, heavily focused on the (still) emerging technologies of autonomous and autonomic systems [25, 26]. Traditional mission concepts, reliant on one large spacecraft, are being complemented with mission concepts that involve several smaller spacecraft, operating in collaboration, analogous to swarms in nature. This offers several advantages: the ability to send spacecraft to explore regions of space where traditional craft simply would be impractical, greater redundancy (and, consequently, greater protection of assets), and reduced costs and risk, to name but a few. Planned missions entail the use of several unmanned autonomous vehicles (UAVs) flying approximately one meter above the surface of Mars,

which will cover as much of the surface of Mars in three seconds as the now famous Mars rovers did in their entire time on the planet; the use of armies of tetrahedral walkers to explore the Martian and Lunar surface; constellations of satellites flying in formation; and the use of miniaturized pico-class spacecraft to explore the asteroid belt.

These new approaches to exploration missions simultaneously pose many challenges. The missions will be unmanned and necessarily highly autonomous. They will also exhibit the classic properties of autonomic systems, being self-protecting, self-healing, self-configuring, and self-optimizing. Many of these missions will be sent to parts of the solar system where manned missions are simply not possible, and to where the round-trip delay for communications to spacecraft exceeds 40 minutes, meaning that the decisions on responses to problems and undesirable situations must be made *in situ* rather than from ground control on Earth. The degree of autonomy that such missions will possess would require a prohibitive amount of testing in order to accomplish system verification. Furthermore, learning and adaptation towards continual improvements in performance will mean that emergent behavior patterns simply cannot be fully predicted through the use of traditional system development methods. The result is that formal specification techniques and formal verification will play vital roles in the future development of NASA space exploration missions.

3.1. ANTS: A Concept Mission

Autonomous Nano Technology Swarm (ANTS) is a joint NASA Goddard Space Flight Center and NASA Langley Research Center collaboration to develop revolutionary mission architectures and exploit artificial intelligence techniques and paradigms in future space exploration. The mission will make use of swarm technologies for both spacecraft and surface-based rovers.

ANTS consists of a number of concept missions:

SARA: *The Saturn Autonomous Ring Array* will launch 1000 pico-class spacecraft, organized as ten sub-swarms, each with specialized instruments, to perform *in situ* exploration of Saturn's rings, by which to understand their constitution and how they were formed. The concept mission will require self-configuring structures for nuclear propulsion and control, which lies beyond the scope of this paper. Additionally, autonomous operation is necessary for both maneuvering around Saturn's rings and collision avoidance.

PAM: *Prospecting Asteroid Mission* will also launch 1000 pico-class spacecraft, but here with the aim of exploring the asteroid belt and collecting data on particular

asteroids of interest. PAM is described below in Section 3.1.1.

LARA: *ANTS Application Lunar Base Activities* will exploit new NASA-developed technologies in the field of miniaturized robotics, which may form the basis of remote landers to be launched to the moon from remote sites, and may exploit innovative techniques (described below in Section 3.1.2) to allow rovers to move in an amoeboid-like fashion over the moon's uneven terrain.

Since SARA and PAM have many issues in common (as regards autonomous operation), we will concentrate on PAM in the following. Section 3.1.2 describes the unique technologies that are planned for the LARA (and other) concept missions.

3.1.1. PAM The ANTS PAM (Prospecting Asteroid Mission) concept mission [8, 9, 25, 26] will involve the launch of a swarm of autonomous pico-class (approximately 1kg) spacecraft that will explore the asteroid belt for asteroids with certain characteristics.

Figure 1 gives an overview of the PAM mission concept [25]. In this mission, a transport ship, launched from Earth, will travel to a point in space where gravitational forces on small objects (such as pico-class spacecraft) are all but negligible. From this point, termed a Lagrangian, 1000 spacecraft, which will have been assembled *en route* from Earth, will be launched into the asteroid belt. As much as 60 to 70 percent of them are expected to be lost during the mission, primarily because of collisions with each other or with an asteroid during exploration operations, since, having only solar sails to provide thrust, their ability to maneuver will be severely limited. Because of their small size, each spacecraft will carry just one specialized instrument for collecting a specific type of data from asteroids in the belt. Approximately 80 percent of the spacecraft will be workers that will carry the specialized instruments (e.g., a magnetometer or an x-ray, gamma-ray, visible/IR, or neutral mass spectrometer) and will obtain specific types of data. Some will be coordinators (called leaders) that have rules that decide the types of asteroids and data the mission is interested in and that will coordinate the efforts of the workers. The third type of spacecraft are messengers that will coordinate communication between the rulers and workers, and communications with the Earth ground station.

The swarm will form sub-swarms under the control of a ruler, which contains models of the types of science that it wants to perform. The ruler will coordinate workers, each of which uses its individual instrument to collect data on specific asteroids and feed this information back to the ruler, who will determine which asteroids are worth examining further. If the data matches the profile of a type of asteroid that is of interest, an imaging spacecraft will be sent to the asteroid to ascertain the exact location and to create a

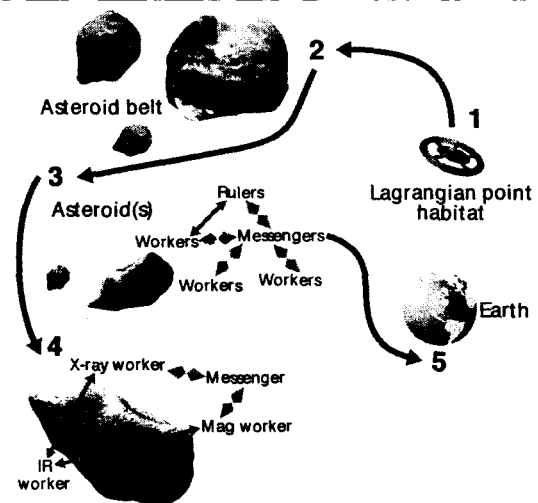


Figure 1. NASA's Autonomous Nano Technology Swarm (ANTS) mission scenario.

rough model to be used by other spacecraft for maneuvering around the asteroid. Other teams of spacecraft will then coordinate to finish mapping the asteroid to form a complete model.

3.1.2. SMART The ANTS SMART (Super Miniaturized Addressable Reconfigurable Technology) architectures were initiated at Goddard Space Flight Center (GSFC) to develop new kinds of structures capable of:

- goal-oriented robotic motion,
- changing form to optimize function (morphological capabilities),
- adapting to new environmental demands (learning and adaptation capabilities), and
- repairing-protecting itself (autonomic capabilities).

The basic unit of the structures is a tetrahedron (Figure 2) consisting of four addressable nodes interconnected with six struts that can be reversibly deployed or stowed. More complex structures are formed from interconnecting these reconfigurable tetrahedra, making structures that are scalable, and leading to massively parallel systems. These highly-integrated 3-dimensional meshes of actuators/nodes and structural elements hold the promise of providing a new approach to robust and effective robotic motion. The current working hypothesis is that the full functionality of such a complex system requires fully autonomous intelligent operations at each node.

The tetrahedron (tet) "walks" by extending certain struts, changing its center of mass and "falling" in the desired direction. As the tetrahedral structure "grows" by interfacing

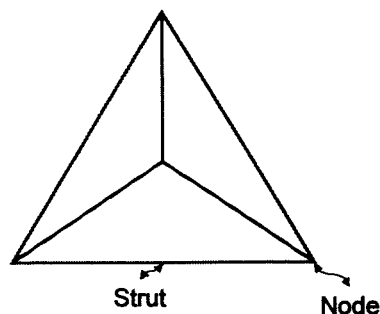


Figure 2. Basic unit of tetrahedral structures.

ing more and more tets, the falling motion evolves to a smoother walking capability, i.e., the smoother walking-climbing-avoiding capabilities emerge from the orchestration of the capabilities of the tetrahedra involved in the complex structure.

Currently, the basic structure, the tetrahedron, is being modeled as a communicating and cooperating/collaborating four-agent system with an agent associated with each node of the tetrahedon. An agent, in this context, is an intelligent autonomous process capable of bi-level deliberative and reactive behaviors with an intervening neural interconnection (the structure of the neural basis function [7]). The node agents also possess social and introspective behaviors. The problem to be solved is to scale this model up to one capable of supporting autonomous operation for a 12-tet rover (a structure realized by the integration of 12 tets in a polyhedral structure). The overall objective is to achieve autonomous robotic motion of this structure. (See <http://ants.gsfc.nasa.gov> to view animations of the tetrahedon-based walking capabilities currently being modeled as multi-agent systems.)

3.2. Other NASA Swarm-Based Missions

An autonomous space exploration system is currently under development at Virginia Tech, funded by the NASA Institute for Advanced Concepts (NIAC).

The system consists of a swarm of low altitude, buoyancy-driven gliders for terrain exploration and sampling, a buoyant oscillating wing that absorbs wind energy, and a docking station that can be used to anchor the energy absorber, charge the gliders, and serve as a communications relay.

The work builds on success with underwater gliders currently used for oceanography research. The intent is to develop low-cost planetary exploration systems that can run autonomously for years in harsh environments such as in the

sulfuric acid atmosphere of Venus, or on Titan (the largest of Saturn's moons).

3.3. NASA Constellations

We may consider constellations—several spacecraft flying together in formation—to be a special case of swarms.

The ST5 mission, for example, which is scheduled for Spring 2006, will launch three identical spacecraft that will fly in a “string of pearls” formation, utilizing a single uplink/downlink to earth. While a mission based on three spacecraft cannot be expected to perform highly distributed work as envisaged in ANTS, for example, it is certainly possible for the large spacecraft (or satellites) to be used in a constellation.

Indeed, this is the approach taken in the NASA Constellation-X mission. Constellation-X involves the use of a small number of telescopes (currently four), in formation and working together to give the equivalent of a single X-ray telescope for observing black holes and other X-ray sources with greater resolution than before possible.

4. Other Applications of Swarms

The behavior of swarms of bees has been studied as part of the BioTracking project at Georgia Tech [1]. To expedite the understanding of the behavior of bees where large scale robust behavior emerges from the simple behavior of individuals, the project videotaped the behavior of bees over a period of time, using a computer vision system to analyze data on sequential movements that bees use to encode the location of supplies of food, etc. The intention is that such models of bee behavior can be used to improve the organization of cooperating teams of simple robots capable of complex operations. A key point is that the robots need not have *a priori* knowledge of the environment, nor is there direct communication between robots in the teams.

Research at Penn State University has focused on the use of particle swarms for the development of quantitative structure activity relationships (QSAR) models used in the area of drug design [6]. The research created models using artificial neural networks and k-nearest neighbor and kernel regression. Binary and niching particle swarms were used to solve feature selection and feature weighting problems.

Particle swarms have influenced the field of computer animation also. Rather than scripting the path of each individual bird in a flock, the Boids project [16] elaborates a particle swarm with the simulated birds being the particles. The aggregate motion of the simulated flock is much like that in nature: it is the result of the dense interaction of the relatively simple behaviors of each of the (simulated) birds, where each bird chooses its own path.

Much success has been reported from the use of Ant Colony Optimization, a technique that studies the social behaviors of colonies of ants, and uses these behavior patterns as models for solving difficult combinatorial optimization problems [11]. The study of ants and their ability to find shortest paths has lead to ACO solutions to the traveling salesman problem, as well as network and internet optimizations [10, 11].

Work at University of California Berkeley is focusing on the use of networks of Unmanned Underwater Vehicles (UUVs). Each UUV has the same template information, containing plans, subplans, etc., and relies upon this and its own local situation map to make independent decisions, which will result in cooperation between all of the UUVs in the network. Experiments involving strategies for group pursuit will be conducted in a shallow water pool.

5. Swarm Technologies Require Autonomicity

5.1. Autonomic Properties of ANTS

The ANTS mission will exhibit almost total autonomy. The mission will also exhibit many of the properties required to qualify it as an *autonomic system* [21, 26, 27].

Self-Configuring: ANTS' resources must be fully configurable to support concurrent exploration and examination of hundreds of asteroids. Resources must be configured at both the swarm and team (sub-swarm) levels, in order to coordinate science operations while simultaneously maximizing resource utilization.

Self-Optimizing: Rulers self-optimize primarily through learning and improving their ability to identify asteroids that will be of interest. Messengers self-optimize through positioning themselves appropriately. Workers self-optimize through learning and experience. Self-optimization at the system level propagates up from the self-optimization of individuals.

Self-Healing: ANTS must self-heal to recover from damage due either to solar storms or (possibly) to collision with an asteroid or other ANTS spacecraft. Loss of a ruler or messenger may involve a worker being "upgraded" to fulfill that role. Additionally, loss of power may require a worker to be killed off.

Self-Protecting: In addition to protection from collision with asteroids and other spacecraft, ANTS teams must protect themselves from solar storms, where charged particles can degrade sensors and electronic components, and destroy solar sails (the ANTS spacecrafts' sole source of power and thrust). ANTS teams must re-plan their trajectories, or, in worst-case scenarios, must go into "sleep" mode to protect their sails and instruments and other subsystems.

The concept of autonomicity can be further elaborated beyond the self-CHOP properties listed above. Three additional self-properties: self-awareness, self-monitoring and self-adjusting, will facilitate the basic self-properties. Swarm (ANTS) individuals must be aware (have knowledge) of their own capabilities and their limitations, and the workers, messengers, and rulers will all be involved in constant self-monitoring and (if necessary) self-adjusting, thus forming a feedback control loop. Finally, further elaborated, the concept of autonomicity would require environmental awareness: the swarm (ANTS) individuals will need to be constantly aware of the environment around them not only to ensure mission success but also to self-CHOP and adapt when necessary.

5.2. Why Other Swarm Based Systems Should be Autonomic

We have argued elsewhere [22] that *all* computer based systems should be autonomic. We can certainly justify this in the case of most NASA missions, due to the high levels of autonomy, the difficulties of dealing with reduced communication bandwidth while at the same time responding rapidly to situations that threaten the mission, and the remoteness of the operation.

Swarms are being used in devising solutions to various problems principally because they present an appropriate model for that problem. We have described in Section 3.1 and Section 4 several application areas of swarm technology where the approach seems to be particularly successful.

But swarms (in nature or otherwise) inherently *need* to exhibit autonomic properties. To begin with, swarms should be self directed and self governing. Recall that this is achieved through the complex behavior that emerges from the combination of several simple behaviors and their interaction with the environment. It can be said that in nature, organisms and groups/colonies of individuals, with the one fundamental goal of survival, would succumb as individuals and even as species without autonomicity. The conclusion that invented swarms with planned mission objectives must similarly possess autonomicity is inescapable.

5.3. Verifying Swarms

As mission software becomes more complex, testing and error-finding also become more difficult. This is especially true of highly parallel processes and distributed computing, both being characteristic of swarm-based systems.

Race conditions in these systems can rarely be found by inputting sample data and checking whether the results are correct. These types of errors are time-based and only occur when processes send or receive data at particular times, or in

a particular sequence, or after learning occurs. To find these errors through testing, the software processes involved have to be executed in all possible combinations of states (state space) that the processes could collectively be in. Because the state space is exponential in the number of states, it becomes untestable with a relatively small number of elements in the swarm. Traditionally, to get around the state-space explosion problem, testers have artificially reduced the number of states of the system and approximated the underlying software using models. Formal methods are proven approaches for ensuring the correct operation of complex interacting systems. Once written, a formal specification can be used to prove properties of a system correct and check for particular types of errors (e.g., race conditions), and can be used as input to a model checker. Verifying emergent behavior is one area that, unfortunately, most formal methods have not addressed well.

The *FAST (Formal Approaches to Swarm Technologies)* project surveyed formal methods techniques to determine whether any would be suitable for verifying swarm-based systems and their emergent behavior [18, 19]. The project found that there are a number of formal methods that support the specification of either concurrency or algorithms, but not both. Though there are a few formal methods that have been used to specify swarm-based systems, the project found only two formal approaches that were used to analyze the emergent behavior of swarms.

Weighted Synchronous Calculus of Communicating Systems (WSCCS), a process algebra, was used by Tofts to model social insects [24], and by Sumpter, et al., to analyze the non-linear aspects of social insects [23]. X-Machines have been used to model cell biology [13, 14], and with modifications, the X-Machines model has potential for specifying swarms. Simulation approaches are being investigated to determine emergent behavior [12]. However, these approaches do not predict emergent behavior from the model, but rather model the emergent behavior after the fact.

The project has defined an integrated formal method, which is appropriate for the development of swarm-based systems [17]. Future work will concentrate on the application of the method to demonstrate its usefulness, and on the development of appropriate support tools.

6. Conclusions

A brief overview of swarm technologies has been presented with emphasis on their relevance for potential future NASA missions. Swarm technologies hold promise for complex exploration and scientific observational missions that require capabilities that would be unavailable in missions designed around single spacecraft.

While swarm autonomy is clearly essential for missions where human control is not feasible (e.g., when communications delays are too great or communications data rates are inadequate for effective remote control), autonomy is essential for survival of individual spacecraft as well as the entire swarm, as a consequence of hostile space environments.

NASA is pursuing further development of formal methods techniques and tools that can be applied in the development of swarm-based systems, to help achieve confidence in their correctness.

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